Energy 36 (2011) 3825–3837

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Exergy analysis of biomass-to-synthetic natural gas (SNG) process via indirect gasification of various biomass feedstock

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ARTICLE INFO

Article history:
Received 23 February 2010
Received in revised form
2 September 2010
Accepted 5 September 2010
Available online 25 October 2010

Keywords:
Biomass
Biofuels
Synthetic natural gas (SNG)
Gasification
Exergy

ABSTRACT

This paper presents an exergy analysis of SNG production via indirect gasification of various biomass feedstock, including virgin (woody) biomass as well as waste biomass (municipal solid waste and sludge). In indirect gasification heat needed for endothermic gasification reactions is produced by burning char in a separate combustion section of the gasifier and subsequently the heat is transferred to the gasification section. The advantages of indirect gasification are no syngas dilution with nitrogen and no external heat source required. The production process involves several process units, including biomass gasification, syngas cooler, cleaning and compression, methanation reactors and SNG conditioning. The process is simulated with a computer model using the flow-sheeting program Aspen Plus. The exergy analysis is performed for various operating conditions such as gasifier pressure, methanation pressure and temperature. The largest internal exergy losses occur in the gasifier followed by methanation and SNG conditioning. It is shown that exergetic efficiency of biomass-to-SNG process for woody biomass is higher than that for waste biomass. The exergetic efficiency for all biomass feedstock increases with gasification pressure, whereas the effects of methanation pressure and temperature are opposite for treated wood and waste biomass.

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1. Introduction

1.1. General background

Major global energy problems related to the use of fossil fuels are a fast depletion and environmental damage due to emission of various gaseous compounds, mainly CO_2, SO_x, and NO_x. Moreover, worldwide energy demand is growing which also increases the need for renewable energy sources. With respect to global issues of sustainable energy, biomass is getting increased attention as a potential source of renewable energy. The key features of biomass are renewability and neutral CO_2 impact. Generally, all organic material that stems from plants, trees, and crops is named biomass. Biomass is a relatively clean feedstock for producing modern energy carriers such as electricity and transportation fuels. Thermochemical biomass conversion, particularly gasification, is considered as the most promising technology for a large scale biomass conversion. Biomass gasification offers a higher efficiency compared to combustion or pyrolysis but this process is still in the early stage of development. During gasification process biomass is partially oxidized to a syngas, which can be used to produce electricity in gas turbines, engines, and fuel cells or chemicals and transportation fuels in catalytic reactions. Transportation fuels derived from biomass, such as methanol, Fischer–Tropsch hydrocarbons and hydrogen are gaining currently more attention as potential substitutes for fossil fuels [1].

Recently, a renewed interest has grown in many countries in Synthetic Natural Gas (SNG) as an energy carrier [2,3]. The original interest in SNG stems from coal-to-SNG technology developed in the early 70s. However, most of this development has been cancelled in the 80s. The only one commercial plant was commissioned in 1984 in Great Plains (North Dakota, United States) and have been producing 4.8 Mio m^3 SNG per day ever since [4].

Nowadays, bio-SNG can be produced from biomass in a renewable way using various routes, including gasification and also anaerobic digestion or supercritical biomass gasification. Today biomass supplies about 50 EJ globally, mainly as the traditional biomass use for cooking and heating. The technical potential of biomass for diverse range of feedstock is estimated between 200 and 500 EJ/year by 2050 (excluding aquatic biomass) [5]. Forestry and agricultural residues and other organic wastes (including MSW (Municipal Solid Waste)) would provide between 50 and 150 EJ/year. Worldwide oil consumption was 161 EJ (82.5 million barrels oil per day) in 2005 according to BP Statistical Review of World Energy.

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doi:10.1016/j.energy.2010.09.026

Nomenclature

ΔH	enthalpy change (kJ/mole)
E_i	exergy flow rate of "i" material stream (MW)
E^Q	thermal exergy flow rate (MW)
E^W	flow rate of work interaction (MW)
Ψ	exergetic efficiency (-)

Acronyms

HHV	higher heating value
ICI	imperial chemical industries
MR	methanation reactor
MSW	municipal solid waste
SNG	synthetic natural gas

The major advantage of SNG as an energy carrier is the potential to use the existing natural gas infrastructure. SNG can replace natural gas as a green alternative in households and can be used as an alternative fuel in transportation. Currently, several research institutes are developing biomass-to-SNG technology, including Energy Research Center of the Netherlands (ECN), Center for Solar Energy and Hydrogen Research (ZSW) Baden Würtenberg, and Paul-Sherrer Institute (PSI) in Switzerland [4]. In the Netherlands annually 3280 PJ of primary energy is consumed whereas natural gas contributes in 46% to this amount. The Dutch Ministry of Economic Affairs has defined the ambition to replace 20% of natural gas by SNG in 2030, and substitution target of 50% has been suggested for 2050 [6]. A 20% substitution would correspond to 300 PJ of SNG with a current annual consumption on natural gas being 1500 PJ. Currently ECN operates a biomass-to-SNG pilot plant unit (Milena indirect gasifier technology) of 160 kg/h (0.8 MW_{th}) input. A demonstration plant of 10 MW_{th} is planned for the near future. The scale foreseen for a commercial SNG production facility is between 50 and 500 MW_{th} which corresponds to 3–30 ton/h of SNG [7].

However, the use of biomass is accompanied by possible drawbacks, mainly limitation of land and water, and competition with food production. The agricultural production of biomass is relatively land intensive and involves high logistics costs due to low energy density of biomass. The average conversion efficiency of sunlight into chemical energy in biomass through photosynthesis is about 0.5–1.0% which is much lower compared to other forms of renewable energy such as photovoltaics or wind energy. For biomass-based systems a key challenge is thus to develop efficient conversion technologies which can also compete with fossil fuels. Moreover, in future more attention should be devoted to conversion of various waste biomass streams, such MSW and sludges, which do not compete with food production.

There are two key aspects in the development of future biomass-to-energy systems, namely development of chemical conversion technologies and selection of the most efficient chains: biomass feedstock-conversion process-biofuel. The first aspect relates to solving relevant chemical and chemical engineering problems, such as the reduction of tar content in the syngas from biomass gasification, design of biomass gasifiers, and development of catalyst for chemical conversion of syngas to biofuels. The scientific challenges belonging to these problems show similar character to those encountered for current fossil fuel technology. On the other hand the scientific and engineering challenges resulting from the second development key-aspect are quite unique for biomass. Due to a large variation of biomass feedstocks, conversion technologies, and biofuels, the future bio-energy systems can be designed almost from scratch. To this end the selection of the most efficient biomass conversion processes and synthesis of biofuels requires a correct use of thermodynamics. The latter aspect forms the main motivation for this paper.

One of the difficulties with measuring energy efficiency is the lack of consensus on the evaluation of performance of different stages of energy systems. Energy efficiency is a rather general term and in practice various performance indicators are used, usually grounded in thermodynamics or economics. Thermodynamic indicators of process performance based on the second law (exergy analysis) are nowadays commonly accepted as the most natural way to measure the performance of different processes, ranging from energy technology, chemical engineering, transportation, agriculture, etc.

1.2. Objectives

The objective of this paper is to evaluate the exergetic efficiency and propose recommendations for improvement of the biomass-to-SNG conversion process via indirect gasification. Various biomass feedstock are used in this study, including virgin biomass – treated wood as well as waste biomass – municipal solid waste and sludge. The final SNG product relates to the Dutch situation, particularly Groningen natural gas. From this point of view the main requirement for the produced SNG is a Wobbe-index of about 44 MJ/Nm^3 which characterizes quality and interchangeability of various gaseous fuels, including natural gas.

The special attention in this paper is devoted to the influence of main process parameters on the overall exergetic efficiency. The investigated process parameters are gasification pressure, pressure in the methanation section, and temperature of the first methanation reactor, which operates as a cooled reactor.

2. Biomass-to-SNG-route

2.1. Main process steps

A block diagram of biomass-to-SNG process is presented in Fig. 1. The principal process steps are biomass gasification, where a syngas is produced, followed by methanation of the produced syngas [6]. A wide range of biomass sources, such as traditional agricultural crops, residues from agriculture and foresting can be used to make SNG. These biomass feedstocks vary greatly in chemical composition, energy content, ash and moisture content. This is generally regarded as a real advantage, because it means that the best and economically attractive feedstock can be selected. In this paper SNG is produced from various biomass feedstock, including treated wood, MSW and sludge.

2.2. Biomass gasification

Generally, several pre-treatment techniques, such as size reduction, drying or torrefaction can be applied before biomass gasification. In the case of SNG production from the treated wood which is relatively dry and high quality feedstock, biomass pre-treatment is not needed. However, in the case of waste biomass (MSW and sludge) which are wet feedstock, biomass pre-

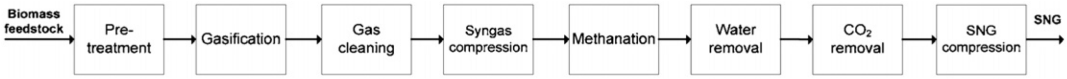

Fig. 1. Block diagram of the biomass-to-SNG process.

treatment includes also drying. Biomass gasification takes place in a gasifier reactor and different gasification technologies are available. From the point of view of heat management during gasification one can distinguish between direct and indirect gasifiers. Gasification of biomass involves endothermic chemical reactions that require heat and produce carbon monoxide, hydrogen and methane. In direct gasifiers biomass gasification takes place in a single reactor where also exothermic oxidation of carbon, present in biomass, into carbon dioxide takes simultaneously place. Direct gasifiers operate usually using air or oxygen as gasifying agents. In this case all heat needed for gasification is produced internally inside the gasifier.

In the case of SNG production the gasifying agent is usually steam, resulting in syngas with relatively high methane content. In this case more heat is needed for gasification compared to gasification using air (oxygen). If a direct gasifier is applied in this case then the extra heat (fuel) has to be added to the gasifier [8]. Alternatively the extra heat can come from the combustion of a part of biomass feedstock, as in an indirect gasifier. An indirect gasifier consists of two separate sections: gasification and combustion zones, as shown schematically in Fig. 2. In the gasification section biomass is gasified using steam as a gasifying medium. The carbon conversion from biomass into syngas is not complete and a part of ungasified biomass (char) is subsequently combusted using air in a combustion section. Heat can be transferred from the combustion to gasification section via a heat carrier, such as sand or olivine, or over an internal gasifier wall. Indirect gasifiers produce two gas products: N_2 free syngas and flue gas. The medium calorific syngas which is N_2 free is an advantage compared to direct gasification. Syngas contains not only major compounds as CO, H_2, CH_4, CO_2, H_2O, but also minor substances, such as particulates, tars, and nitrogen and sulphur compounds. They have to be removed before methanation using appropriate equipment such as cyclones, catalytic tar removal and catalytic guard beds, respectively.

2.3. Syngas methanation

Clean syngas is compressed and enters the methanation synthesis section. This section consists of three catalytic reactors in series (Ni-based catalyst), according to ICI (Imperial Chemical Industries) technology [9]. In the reactors CO, CO_2, and H_2 are converted into CH_4 according to the following exothermic reactions:

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H = -206 \text{ kJ/mol} \tag{1}$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad \Delta H = -165 \text{ kJ/mol} \tag{2}$$

In addition to the above-mentioned reactions undesired carbon formation can also occur:

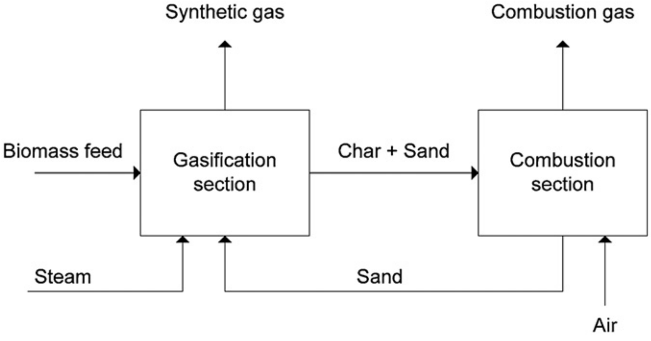

Fig. 2. Schematic representation of indirect biomass gasifier.

$$2\,CO \leftrightarrow CO_2 + C_{(s)} \quad \Delta H = -172 \text{ kJ/mol} \tag{3}$$

$$CO + H_2 \leftrightarrow C_{(s)} + H_2O \quad \Delta H = -131 \text{ kJ/mol} \tag{4}$$

Carbon formation can be suppressed by steam addition to methanation synthesis section. The gas inlet temperatures in methanation reactors are according to the ICI technology: 398, 325, and 300 °C, respectively.

2.4. SNG conditioning

After methanation section the raw SNG gas contains not only methane as the main compound, but also a substantial amounts of water and carbon dioxide. These compounds have to be removed in order to meet quality requirements of the final SNG such as Wobbe-index. Water is removed by gas cooling and subsequent condensation. Carbon dioxide can be removed using various separation methods, including physical or chemical absorption using an efficient CO_2 solvent or cryogenic cooling. During CO_2 separation also some part of methane may be removed together with CO_2-rich stream which leads to some loss of produced methane. Finally, SNG is compressed into high pressure as desired for applications based on Groningen gas.

3. Process description

3.1. Process modelling for woody biomass as a feedstock

The biomass-to-SNG process is simulated using the program Aspen Plus. The purpose of this analysis is to demonstrate the efficiency of the process and determine the optimal conditions. First, mass and energy balances have been modeled for the process flowsheet composed of the selected components and subsequently the exergy analysis has been performed. Fig. 3 shows the flowsheet of the biomass-to-SNG process which integrates biomass gasification with methanation section. The biomass feedstock is treated wood with composition summarized in Table 1.

Biomass at the flow rate of 10 kg/s enters the indirect gasifier which consists of two separate sections: gasification and combustion. Steam is used in the gasification section to gasify biomass at constant temperature of 737 °C. The gasification pressure was varied in the range 1–15 bar (7 bar at the standard process conditions). Unconverted biomass (char) which leaves the gasification section is combusted in the combustion section at temperature 787 °C using air. Heat resulting from char combustion is directly transferred to the gasification section. The enthalpy of a hot flue gas leaving the combustion section is used to preheat combustion air. Both sections are modeled using a Gibbs-reactor module from Aspen Plus. The chemical equilibrium approach is commonly applied in the literature to model biomass gasifiers [10–13]. This model predicts correctly orders of magnitude and composition trends but when gasifying with steam it overestimates the yield of H_2 and CO whereas the yield of CH_4 is underestimated [14]. The influence of such differences on the performance of biomass-to-SNG process using direct gasification was previously discussed [8]. It was shown that the flow rate of produced SNG was not influenced by a gasification model used whereas the error in predicted exergetic process efficiency was less than 1%.

Raw syngas leaving gasifier is cooled in a syngas cooler where steam needed for biomass gasifier is also produced (within the control volume studied). Syngas contains major gas compounds such as CO, H_2, CH_4, CO_2, H_2O, but also impurities such as tars, particulates, and nitrogen and sulfur compounds. Although the impurities are present in a relatively small amount, they may cause problems in the subsequent process units, particularly methanation section. Syngas impurities are removed in the syngas cleaning unit

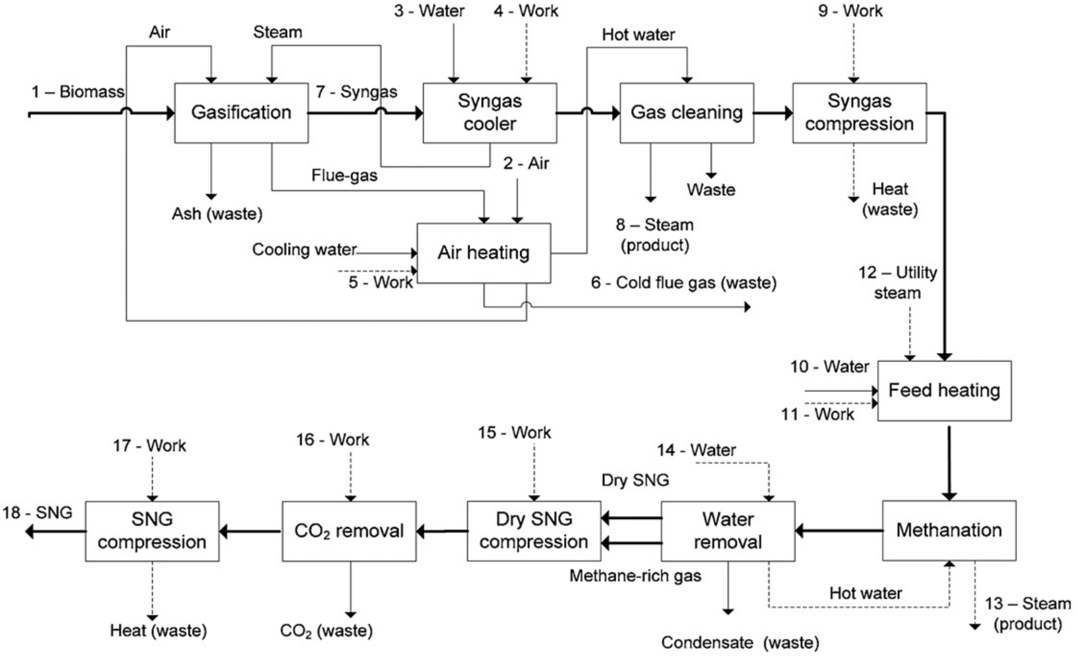

Fig. 3. Flowsheet of the biomass-to-SNG process.

consisting of a cyclone (particulates), absorption unit (tars) and guard beds reactors (nitrogen and sulfur compounds). In a cleaning section syngas is additionally cooled till 140 °C which enables an additional heat recovery resulting in steam production.

The next major step in a biomass-to-SNG process is syngas methanation which is performed at high pressure in the range of 15–30 bar (20 bar at the standard process conditions for woody biomass). Syngas compression before methanation section is modeled depending on the ratio of methanation pressure to gasification pressure, being a single compressor or a multistage compressor, respectively. Methanation section is modeled based on the steam-moderated ICI-high temperature once-through process. Steam used for methanation, generated in a separate steam generator (outside of the control volume studied), is injected to a feed heating unit preceding the methanation section. The main function of steam added to methanation is prevention of carbon formation which can block catalytic activity. According to the ICI process the methanation section consists of three reactors in series with two intercoolers placed in-between in order to control the temperature of gas entering the 2nd and 3rd methanation reactors. The inlet gas temperature for the 1st methanation reactor (MR) is 398 °C, for the 2nd – 325 °C, and for the 3rd – 300 °C. In all methanation reactions heat is generated due to exothermic chemical reactions Eqs. (1–4). In methanation section catalyzed water–gas shift reaction also occurs:

$$CO + H_2O \leftrightarrow H_2 + CO_2 \quad \Delta H = -41\ \text{kJ/mol} \qquad (5)$$

Methanation process is positively influenced by low temperature and therefore temperature in methanation reactors is controlled in order not to exceed the desired temperatures levels, namely 729 °C in the 1st reactor, 590 °C – in the 2nd reactor and 425 °C – in the 3rd reactor. Moreover, cooling of reactors lowers the risk of overheating of catalyst leading to its deactivation. The first methanation reactor is directly cooled as in this reactor methane conversion is relatively high. At the standard conditions of woody biomass the 1st MR operates at 610 °C. The 2nd and 3rd reactors operate at lower temperature as adiabatic reactors. The heat recovered from the cooling of the 1st reactor and from two intercoolers is used to produce steam. The produced steam can be considered as an additional product of the biomass-to-SNG process.

The raw SNG leaving methanation section contains methane as the main component but also substantial amounts of water and carbon dioxide, which have to be removed. Water is present as a result of steam addition for methanation and also as a product of chemical reactions. A part of carbon dioxide in raw SNG comes from syngas, and other part – from production in water–gas shift reaction Eq. (5). Water is removed by cooling down raw SNG at temperature 28 °C in two flash units. The first flash unit operates at 20 bar and produces a dry SNG stream whereas the second flash unit operates at lower pressure of 5 bar and produces a methane-rich gas.

Dry raw SNG is subsequently compressed up to 50 bar that is required for absorption of carbon dioxide. Carbon dioxide is separated by physical absorption using Selexol (dimethylether of polyethylene glycol) as an efficient CO_2 solvent [15]. Absorption of CO_2 takes place counter-currently in the absorber column. CO_2-rich solvent from the absorber column contains a considerable amount of methane which is recovered in order to reduce methane loss in the process. To this end CO_2-rich solvent enters a flash unit where at lower pressure a methane-rich gas is separated from the remaining the CO_2-rich solvent. The absorption conditions are adjusted in such a way that the outlet SNG stream from the Selexol process meets a particular value of Wobbe-index, namely 44 MJ/Nm^3.

Table 1
Properties of biomass feedstock.

		Treated wood	MSW	Sludge
Proximate analysis				
Moisture	wt% wet	14.8	38.5	32.1
Volatile matter	wt% daf (dry ash free)	80.3	–	88.2
Ash	wt% dry	4.9	44.2	35.1
Ultimate analysis				
Carbon	wt% daf	51.4	55.2	50.2
Hydrogen	wt% daf	6.07	1.72	7.15
Oxygen	wt% daf	41.3	38.53	35.3
Nitrogen	wt% daf	1.24	1.95	5.26
Sulfur	wt% daf	0.10	1.40	1.76
Chlorine	wt% daf	9.9×10^{-2}	1.27	0.28
Fluorine	wt% daf	3.0×10^{-3}	0.04	0.03
HHV	MJ/kg dry	19.69	10.45	13.59

Finally, produced SNG is compressed up to 66 bar by using a single stage compressor. Table 2 summarizes temperature, pressure and mass flow rate of the main process streams at the standard process conditions: gasification pressure 7 bar, methanation pressure 20 bar, temperature of the 1st methanation reactor 610 °C.

3.2. *Exergetic efficiency*

The mass and energy balances obtained from Aspen Plus simulations form the basis for exergy analysis. Exergy of all process streams (mass streams – including biomass, and heat and work) is calculated according to the method described by Szargut [16,17] and recently updated by Rivero [18,19]. Chemical exergy of biomass is evaluated using the statistical correlation for technical fuels using the higher heating value of biomass indicated in Table 1. Table 2 summarizes exergy flow rate of the main process streams at the standard process conditions for treated wood as biomass feedstock.

Exergy analysis is performed for the overall biomass-to-SNG process as well as for main process units indicated in Fig. 2. The overall exergetic efficiency Ψ is defined as the ratio between useful exergy output from the process and the necessary exergy input to this process:

$$\Psi = \frac{E_{\mathrm{SNG}} + \sum\limits_{\mathrm{out}} E_{\mathrm{steam,n}}}{\sum\limits_{\mathrm{in}} E_{\mathrm{i}} + \sum\limits_{\mathrm{in}} E_{\mathrm{j}}^{\mathrm{Q}} + \sum\limits_{\mathrm{in}} E_{\mathrm{k}}^{\mathrm{W}}} \tag{6}$$

where E_{SNG} is the exergy flow rate of the product SNG stream, $\sum\limits_{\mathrm{out}} E_{\mathrm{steam,n}}$ is the sum of exergy flow rate produced steam streams, $\sum\limits_{\mathrm{in}} E_{\mathrm{i}}$ is the exergy flow rate of all entering material streams, $\sum\limits_{\mathrm{in}} E_{\mathrm{j}}^{\mathrm{Q}}$ and $\sum\limits_{\mathrm{in}} E_{\mathrm{k}}^{\mathrm{W}}$ are the sums of all thermal exergy and work entering the process, respectively.

The efficiency Ψ given by Eq. (6) includes produced steam from gas cleaning and methanation units as the additional useful process products, in addition of the main SNG product.

The exergetic process performance is also evaluated using another criterion, namely specific irreversibility (internal exergy losses) per unit volume of produced SNG (MJ/Nm^3).

4. Results and discussion of exergy analysis for woody biomass-to-SNG

The standard process conditions used in simulation of treated wood-to-SNG process were: gasifier pressure 7 bar, methanation pressure 20 bar, and temperature in the 1st methanation reactor (MR) 610 °C. In the subsequent process simulations one of the above-mentioned parameters was varied whereas the remaining two were kept constant. During the simulations the gasification pressure was varied between 1 and 15 bar (for the standard values of methanation pressure 20 bar and temperature in the 1st MR 610 °C), the methanation pressure was varied between 15 and 25 bar (for the standard values of gasification pressure 7 bar and temperature in the 1st MR 610 °C), and the temperature in the 1st methanation reactor was varied between 500 and 610 °C (for the standard values of gasification pressure 7 bar and methanation pressure 20 bar).

4.1. *Mass flow rate and composition of produced SNG*

Table 3 summarizes for all investigated process conditions mass and volume flow rates, composition of produced SNG, syngas and methanation effluent composition, temperature in all methanation reactors, contribution of methane produced in gasifier as well as in all methanation reactors, and total process irreversibilities (internal exergy losses). Table 3 indicates that increasing gasification pressure has a positive influence on the mass flow rate of produced SNG whereas the SNG composition remains almost the same for all investigated gasifier pressures. This effect can be explained by increased carbon conversion for higher gasifier pressure, as shown in Fig. 4a. Table 3 also indicates that increasing methanation pressure as well decreasing temperature in the 1st methanation reactor have a positive influence on the mass flow rate of produced SNG. All these effects can be explained by shift of the chemical equilibrium towards the product side in chemical reactions taking place in the methanation section, see Eqs. (1–5). At higher methanation pressure and lower methanation temperature more methane is produced leading to methane-rich SNG stream. It is interesting to note that the majority of methane is produced in the gasifier (particularly at higher gasification pressure and in the first methanation reactor (particularly at lower temperature in this reactor). The amounts of methane produced in the 2nd and 3rd methanation reactors are lower but still important.

The positive effect of gasification pressure on carbon conversion in the gasifier (see Fig. 4a) can be explained by the higher partial pressure of gaseous reactants in biomass gasification reactions:

$$\text{heterogeneous methanantion}: \ C_{(s)} + 2H_2 \leftrightarrow CH_4 \tag{7}$$

$$\text{homogeneous methanantion}: \ CO + 3H_2 \leftrightarrow CH_4 + H_2O \tag{8}$$

Table 2

Temperature, pressure, mass flow rate, exergy flow rate and specific exergy of mains streams of the treated wood-to-SNG process at standard process conditions (gasifier pressure 7 bar, methanation pressure 20 bar, temperature 1st methanator 610 °C).

No.	Stream	Input/product	T (°C)	Pressure (bar)	Mass flow rate (kg/s)	Exergy flow rate (MW)	Specific exergy (kJ/kg)
1	Biomass	Input	25	1	10.0	181.2	18,120
2	Air	Input	25	1	13.0	0	0
3	Water	Input	25	7	2.52	0.002	0.79
4	Pumping work	Input	–	–	–	0.004	–
5	Compression work	Input	–	–	–	3.7	–
6	Cold flue gas	Ouput	50	7	14.27	3.2	224.2
7	Syngas		737	7	11.25	149.9	13,324
8	Steam	Product	122	1	3.0	1.6	593.3
9	Compression work	Input	–	–	–	3.8	–
10	Water	Input	25	7	2.16	0.001	0.46
11	Pumping work	Input	–	–	–	0.011	–
12	Steam	Input	418	1	9.03	7.3	808.4
13	Steam	Product	162	1	22.13	12.7	573.9
14	Water	Input	25	1	–	0.7	–
15	Compression work	Input	–	–	–	1.0	–
16	Compression and pumping work	Input	–	–	–	12.6	–
17	Compression work	Input	–	–	–	0.1	–
18	SNG	Product	63	66.0	2.57	105.1	40,895

Table 3
Influence of gasification pressure, methanation pressure, and temperature in the 1st methanation reactor (MR) on the main characteristics of treated wood-to-SNG process.

	Gasification pressure (bar)					Methanation pressure (bar)			Temperature 1st methanation reactor (°C)			
	1	5	7	10	15	15	20	25	500	550	610	650
SNG produced												
Mass flow rate (kg/s)	2.37	2.53	2.57	2.62	2.67	2.48	2.57	2.62	2.65	2.64	2.57	2.45
Volume flow rate (Nm^3/s)	3.30	3.51	3.58	3.65	3.73	3.57	3.58	3.58	3.57	3.57	3.58	3.56
SNG composition (mol%)												
CO	0.17	0.17	0.16	0.16	0.16	0.28	0.16	0.11	0.05	0.07	0.16	0.39
CO_2	7.52	7.70	7.70	7.73	7.73	7.07	7.70	8.03	8.36	8.24	7.70	6.82
H_2	6.32	6.33	6.54	6.73	6.90	9.3	6.54	5.07	3.53	4.19	6.54	10.3
N_2	2.61	2.45	2.40	2.35	2.29	2.40	2.40	2.40	2.41	2.41	2.40	2.40
CH_4	83.4	83.4	83.2	83.0	82.9	80.9	83.2	84.4	85.7	85.1	83.2	80.2
Wobbe-index (MJ/Nm^3)	44	44	44	44	44	44	44	44	44	44	44	44
Methanator temperature (°C)												
1st MR (°C)	610	610	610	610	610	610	610	610	500	550	610	650
2nd MR (°C)	490	490	490	489	489	501	490	481	390	429	490	536
3rd MR (°C)	363	363	363	364	364	379	363	353	317	331	363	399
Contribution to total CH_4 produced (%)												
Gasifier	9.0	30.6	36.9	43.8	51.6	37.2	36.9	36.8	36.6	36.7	36.9	37.3
1st MR	72.2	50.5	43.7	36.4	28.2	40.9	43.7	45.6	56.0	51.6	43.7	36.5
2nd MR	13.4	13.5	13.8	14.1	14.4	14.9	13.8	13.0	5.8	9.0	13.8	17.5
3rd MR	5.4	5.5	5.6	5.7	5.8	7.0	5.6	4.6	1.6	2.8	5.6	8.7
Total process irreversibilities (MW)	89.5	82.0	80.3	78.9	79.5	82.4	80.3	79.8	77.9	78.6	80.3	84.1
Syngas composition (mol%)												
CO	35.9	23.5	20.9	18.3	15.6	20.9	20.9	20.9	20.9	20.9	20.9	20.9
CO_2	5.86	12.6	13.9	15.3	16.7	13.9	13.9	13.9	13.9	13.9	13.9	13.9
H_2	49.5	40.4	37.6	34.4	30.7	37.6	37.6	37.6	37.6	37.6	37.6	37.6
H_2O	6.00	16.0	18.6	21.3	24.3	18.6	18.6	18.6	18.6	18.6	18.6	18.6
N_2	0.61	0.56	0.56	0.55	0.55	0.56	0.56	0.56	0.56	0.56	0.56	0.56
CH_4	2.06	6.87	8.33	10.0	11.9	8.33	8.33	8.33	8.33	8.33	8.33	8.33
Methanation effluent composition (mol%)												
CO	0.04	0.04	0.04	0.04	0.04	0.07	0.04	0.03	0.01	0.01	0.04	0.1
CO_2	23.2	23.2	22.8	22.4	22.0	22.8	22.8	22.7	22.1	22.6	22.8	22.8
H_2	1.64	1.64	1.66	1.68	1.69	2.34	1.66	1.29	0.87	1.06	1.66	2.58
H_2O	48.6	48.8	49.9	50.8	51.6	49.4	49.9	50.2	51.8	50.6	49.9	49.2
N_2	0.69	0.64	0.62	0.59	0.57	0.62	0.62	0.62	0.60	0.62	0.62	0.62
CH_4	25.8	25.6	25.0	24.5	24.0	24.7	25.0	25.2	24.6	25.1	25.0	24.6

$$\text{heterogeneous oxidation}: \ C_{(s)} + 1/2\,O_2 \leftrightarrow CO \qquad (9)$$

$$\text{homogeneous oxidation}: \ CO + 1/2\,O_2 \leftrightarrow CO_2 \qquad (10)$$

The chemical thermodynamics and kinetics of above specified reactions is favored by higher gasification pressure, and consequently higher partial pressure of reactants, due to decrease of number of moles in these reactions.

The increased carbon conversion in the gasifier leads also to an increased SNG yield produced from biomass, as shown in Fig. 4b. The SNG yield is defined as the ratio between mass flow of the final SNG product and the mass flow rate of the biomass feed. Fig. 4b shows also methane losses during separation of CO_2 from methane in the raw SNG stream leaving methanation section. Methane loss is defined as the ratio between the amount of methane lost with the CO_2-rich stream and the amount of methane present in the raw SNG gas leaving the methanation. Methane loss decreases with gasification pressure as at these process conditions raw SNG gas contains less CO_2 and then a smaller amount of Selexol solvent is needed in the absorption unit.

4.2. Influence of gasification pressure

Fig. 5a shows the positive influence of the gasification pressure on the exergetic efficiency Ψ of the biomass-to-SNG process. The increase of the exergetic efficiency with gasification pressure is caused by two effects. Firstly, it is an increase of SNG production rate with increasing gasification pressure (see Table 3), and secondly – it is the reduced exergy input to the process. The relatively high value of exergetic efficiency can give the impression that this process is more efficient than modern power stations. It should be noted that in biomass-to-SNG process the chemical exergy of biomass is converted into chemical exergy of SNG whereas in power stations chemical exergy of a fuel is converted into electricity. If subsequently SNG would be converted into other form of energy, such as electrical of mechanical, then the overall efficiency 'biomass-to-energy' will be lower.

Fig. 5a shows also the specific process irreversibility I (internal exergy losses) per unit volume of produced SNG. The specific irreversibility decreases with increasing gasification pressure what is due to the decrease of the total process irreversibilities and increase of volume flow rate of produced SNG with gasification pressure (see Table 3).

Fig. 5b clearly indicates that the largest internal exergy losses (irreversibilities) for treated wood as a feedstock take place in the biomass gasifier, methanation section and CO_2 removal unit using Selexol absorption process. Exergy losses in gasifier accounts for about half of the total process exergy losses. Irreversibilities in the gasifier decrease with gasification pressure due to higher amount of syngas with high methane content and H_2/CO ratio, which gives high exergy output at high gasification pressure. Methanation section is from the point of view of irreversibilities favored by high gasification pressure due to increase in syngas flow rate. In the CO_2 absorption process irreversibility increases with gasification pressure due to higher CO_2 separation load.

4.3. Influence of methanation pressure

Fig. 6a,b show the influence of pressure in methanation section on the exergetic performance of biomass-to-SNG process.

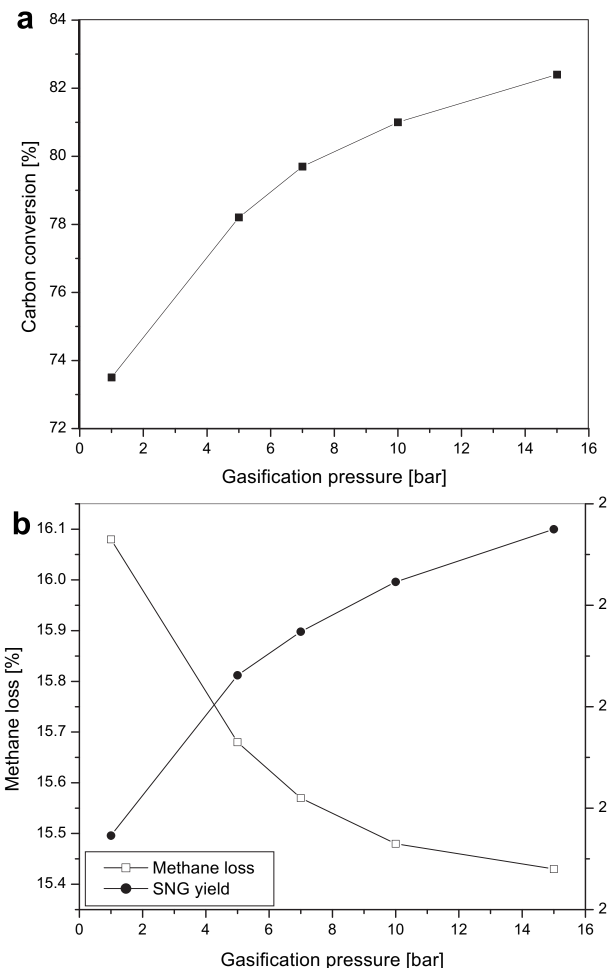

Fig. 4. Influence of gasification pressure for woody biomass on: a) – carbon conversion in the gasifier and b) – SNG yield and methane losses during CO_2 removal (at standard process conditions).

Methanation pressure has a slight positive influence on the exergetic efficiency Ψ for treated wood, as shown in Fig. 6a (the effect of methanation pressure for MSW and sludge is discussed later in Section 5.3). This corresponds to higher methane content in the final SNG product. Fig. 6a shows also that specific process irreversibility for treated wood decreases with increasing methanation pressure. This effect is mainly due to the decrease of the total process irreversibilities with methanation pressure whereas the volume flow rate of produced SNG remains almost the same (see Table 3).

It is interesting to note that irreversibilities in methanation section for treated wood increase with methanation pressure, as shown in Fig. 6b. The exergy of methanation effluent increases with methanation pressure due to the increase in its methane content. At the same time, larger amount of heat has to be removed from the first methanation reactor to maintain the effluent temperature at 610 °C. Unlike the first methanator, the cooling duty of both intercoolers between the 2nd and 3rd methanator decreases due to lower adiabatic temperature rise in these reactor. All these contributions slightly increase irreversibility in the methanation section. In contrast to other process units the irreversibility in the CO_2 Selexol absorption unit decreases with methanation pressure because of the decrease in the extent of CO_2 separation to obtain a Wobbe-index of 44 MJ/Nm^3.

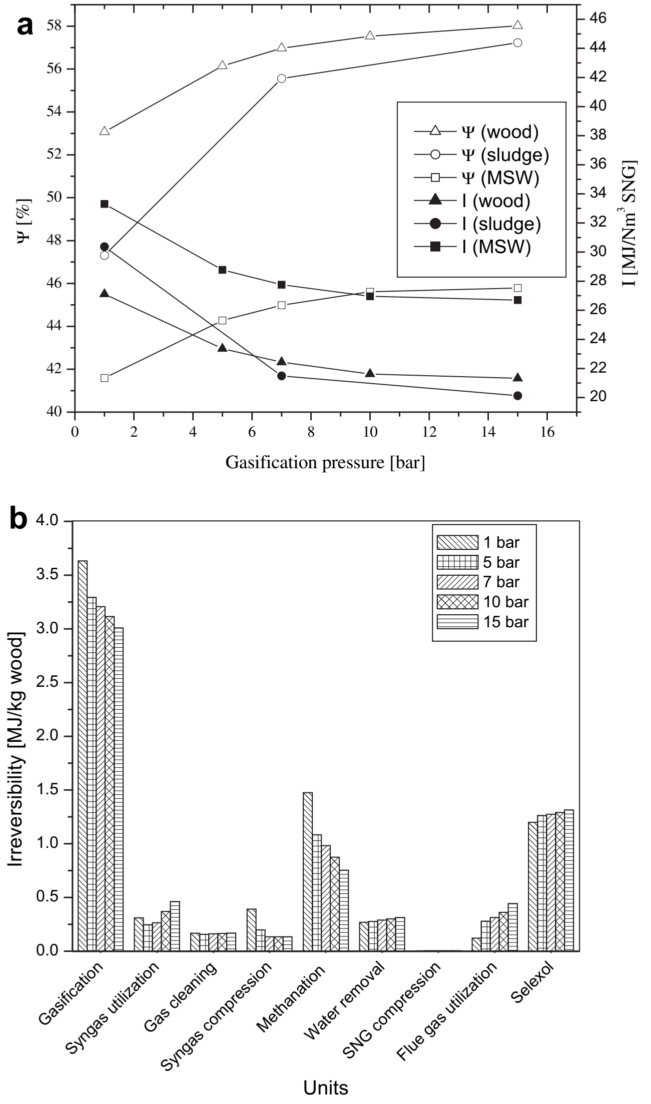

Fig. 5. Influence of gasification pressure on exergetic performance of the biomass-to-SNG process: a) – exergetic efficiency and specific irreversibility, b) – internal exergy losses in process units (at standard process conditions) for woody biomass.

4.4. Influence of temperature in the first methanation reactor

In this part of the study gasification pressure and methanation pressure were kept constant at 7 and 20 bar, respectively, corresponding to the standard process conditions for woody biomass. The investigated temperature range in the first methanation reactor was from 500 to 650 °C. The first reactor was cooled in order to keep its temperature at the desired level whereas the 2nd and 3rd reactors operated adiabatically. Fig. 7a,b shows the influence of the temperature in the 1st methanation reactor on the exergetic performance of the biomass-to-SNG process.

The exergetic efficiency Ψ for treated wood decreases with increasing temperature in the 1st methanation reactor (the effect of methanation temperature for MSW and sludge is discussed later in Section 5.3). At higher temperatures methanation effluent has a higher exergetic value due to relatively large CO and H_2 concentrations which cause slight decrease in the irreversibilities in the methanation section with temperature. However, at higher temperature methanation effluent contains relatively low methane and high CO_2 concentrations which lead to more methane losses

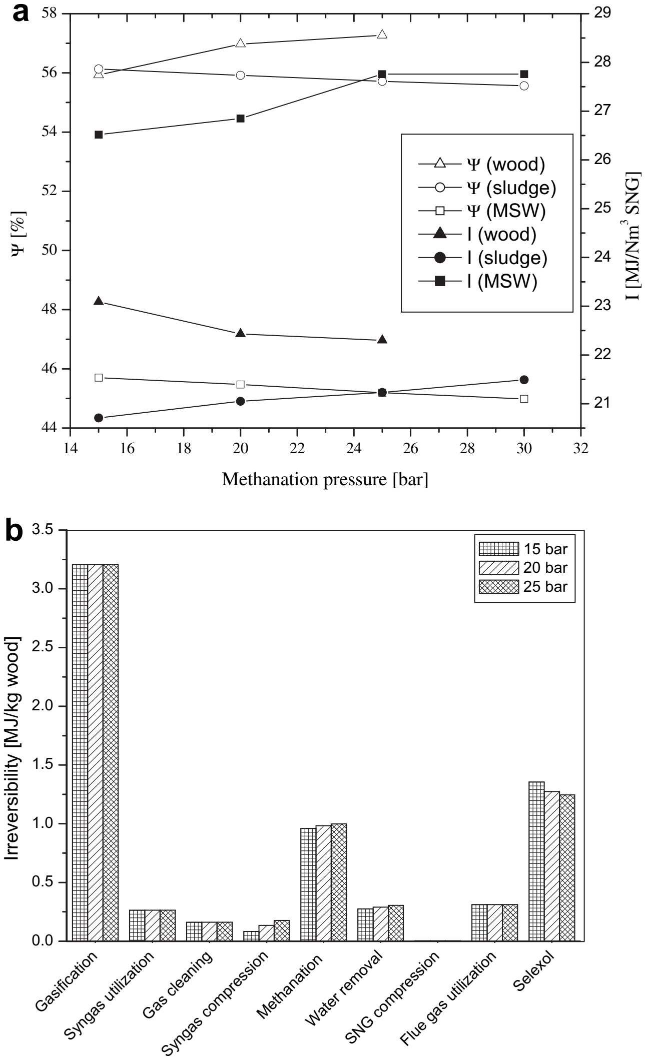

Fig. 6. Influence of methanation pressure on exergetic performance of the biomass-to-SNG process: a) – exergetic efficiency and specific irreversibility, b) – internal exergy losses in process units (at standard process conditions) for woody biomass.

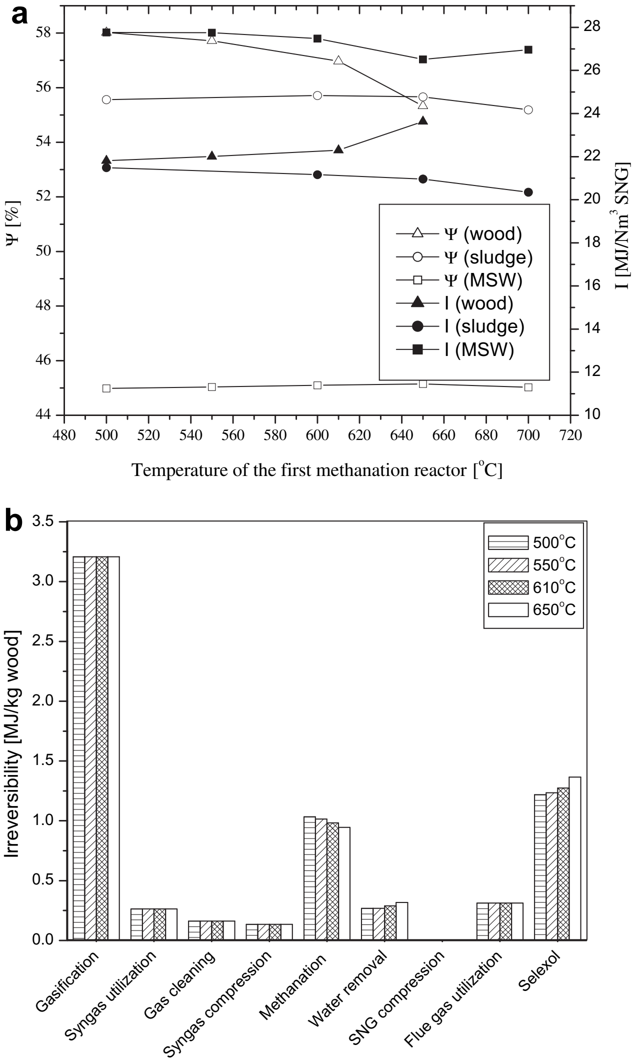

Fig. 7. Influence of temperature in the first methanation reactor on exergetic performance of the biomass-to-SNG process: a) – exergetic efficiency and specific irreversibility, b) – internal exergy losses in process units (at standard process conditions) for woody biomass.

during Selexol process and consequently increase of irreversibility during the subsequent separation of CO_2 and methane.

Fig. 7a shows also that specific process irreversibility for treated wood increases with increasing methanation temperature. This effect is mainly due to the increase of the total process irreversibilities with temperature in the 1st methanation reactor whereas the volume flow rate of produced SNG remains almost the same (see Table 3).

5. Results and discussion of exergy analysis for waste biomass (MSW, sludge)-to-SNG

Table 1 shows that the properties of virgin biomass (treated wood) and waste biomass (MSW and sludge) differ substantially in moisture and ash content. Treated wood is a relatively dry feedstock with low ash content. Moreover, waste biomass contains more impurities, particularly N, S, Cl and F that treated wood. The results of ultimate analysis indicate that MSW has a much lower hydrogen/carbon ratio than treated wood and sludge. It can be expected that all these differences can influence the performance of waste biomass-to-SNG process compared to that of treated wood-to-SNG, as discussed in section 4. Waste biomass-to-SNG process is modeled using the flowsheet shown in Fig. 2 with two modifications: pre-drying of biomass before gasification and replacing Selexol method for CO_2 separation from methanantion effluent by cryogenic separation.

5.1. Modification of waste biomass-to-SNG process: feedstock drying

Waste biomass is more wet feedstock than treated wood and therefore drying of biomass before gasification is desired. Even though drying consumes a considerable amount of energy, it increases biomass energy content, which can lead to higher gasification efficiency [20,21]. Gasification of drier biomass yields lower H_2 content in syngas, which might be undesirable for methanation process. Furthermore, drying costs increase steeply below 10 wt% moisture [20].

In this paper waste biomass feedstock is dried directly before gasifier using atmospheric air as a drying agent, whose inlet and outlet temperature were 237 °C and 110 °C, respectively. Air flow rate was adjusted to achieve the targeted water content in dried biomass, which was varied between 10 and 20 wt% water. Dry feedstock is than fed to the gasification section.

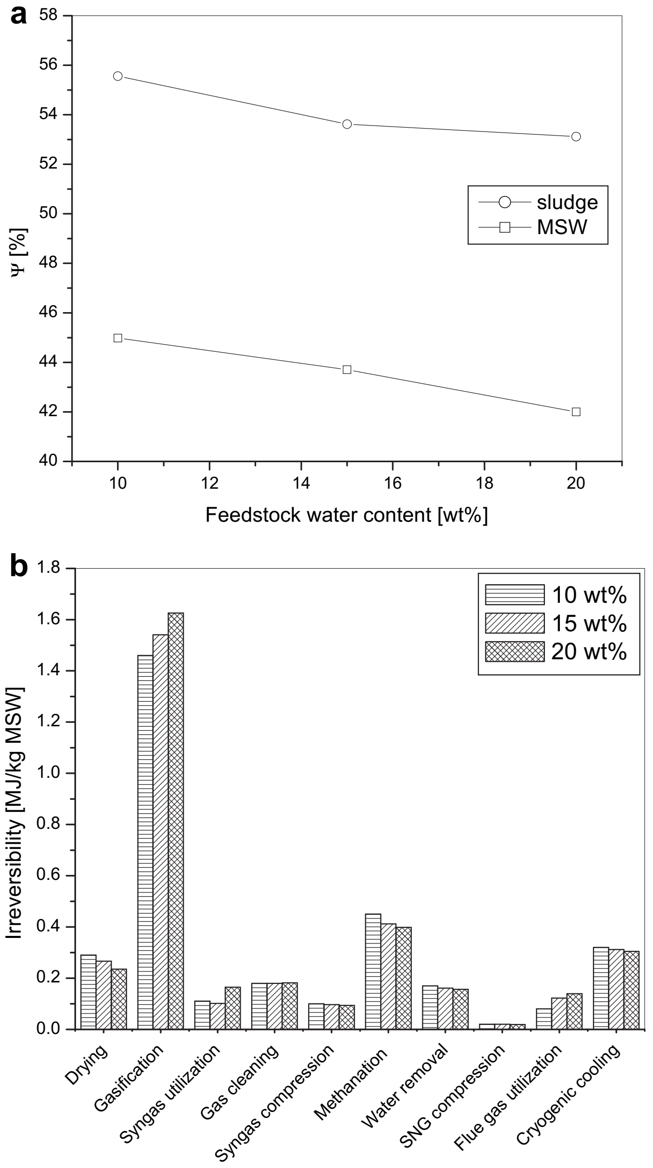

Fig. 8. Effect of feedstock drying on exergetic performance of waste biomass-to-SNG process: a) – exergetic efficiency, b) – internal exergy losses in process units (at standard process conditions) for MSW.

Fig. 8 shows the effect of water content in waste biomass after drying on exergetic performance of biomass-to-SNG process. This figure refers to the standard process conditions for waste biomass which are: gasifier pressure 7 bar, methanation pressure 30 bar, and temperature in the 1st methanation reactor (MR) 500 °C. Fig. 8a clearly illustrates that drying improves exergetic efficiency of overall biomass-to-SNG process for MSW and sludge. The explanation of the positive effect of drying can be found in Fig. 8b where the process irreversibilities are shown for drying of MSW for various values of water content in dried MSW. Internal exergy losses in the gasification unit are largely reduced for dried MSW what mainly contributes to reduction of overall exergy losses. The reduction of exergy losses in the gasification unit is due to higher carbon conversion in the gasifier because a smaller amount of energy is required to bring the feed to the gasification temperature. Consequently more heat is available to conduct gasification reactions and more carbon can be converted into CO, CO_2, and methane. Unlike gasification, drying increases the internal exergy losses in the methanation unit as depicted in Fig. 8b. Drying can improve methane synthesis, which results in the increase of methane content in the methanation effluent stream. However, the overall methanation process becomes less efficient because of the increased heat transfer in the methanation feed heater, as well as in the first methanator and in the intercoolers. As the irreversibility due to heat transfer is higher than methane formation, the efficiency of the overall methanation process decreases.

The effect of drying on the internal exergy losses for sludge-to-SNG process is similar to that shown in Fig. 8b for MSW. Therefore waste biomass: MSW and sludge containing 10 wt% water after drying were chosen for the subsequent assessment of the other process parameters.

5.2. *Modification of waste biomass-to-SNG process: CO_2 separation from methanation effluent by cryogenic separation*

Table 1 shows that both waste biomass feedstock: MSW and sludge have substantial nitrogen content. Sludge has the highest nitrogen content whereas in the case of MSW nitrogen content is higher than that of hydrogen. Compared to treated wood it can be expected that also SNG produced from waste biomass will have higher nitrogen content. In order to reach a prescribed value of Wobbe-index, a considerable amount of CO_2 has to be removed from methanation effluent in the upgrading process, which leads also to increase in methane loss. Moreover, MSW has higher carbon/hydrogen ratio compared to that of treated wood, what leads to higher formation of CO_2 in the gasification section. Therefore CO_2 separation load is in this case higher which results in higher methane loss due to high pressure required for removing CO_2 using Selexol method which was used for treated wood.

In order to minimize methane losses during CO_2 separation from methanation effluent other separation methods have to be considered, such as chemical absorption or cryogenic cooling. The preliminary evaluation showed that chemical absorption of CO_2 in typical amine solutions (e.g. monoethanolamine MEA or n-methyldiethanolamine MDEA) is not suitable due to high water content in produced SNG which properties are out of specification. Selexol solvent dissolves not only CO_2 but also water whereas amine solutions dissolve mainly CO_2 but less water.

On the other hand the comparison between Selexol method and cryogenic cooling for CO_2 separation for waste biomass shows that typical methane loss in this process step is 35–37% using Selexol method and 12–17% using cryogenic cooling. In the case of treated wood methane losses using Seloxol method are 15–16% (see Fig. 4b) what can be considered as a reasonable level. Therefore cryogenic cooling is selected for waste biomass as a CO_2 separation method from methanation effluent. Modeling of cryogenic cooling has the same principle as water removal, where the gas stream is cooled to a particular temperature to condense CO_2. Two atmospheric coolers in series are used to reduce methane loss due to its solubility in the liquid phase. The first condenser cools the gas to −83 °C and −73 °C for MSW and sludge, respectively, whereas the second condenser then brings the gas stream to a temperature at which SNG requirement is specified by Wobbe-index of 44 MJ/Nm^3. The total exergy input for cryogenic cooling is less than that of high pressure Selexol method because electricity consumption for refrigeration is quite moderate.

5.3. *Effect of process conditions: gasification and methanation pressure, and temperature in the first methanation reactor*

Fig. 5a shows the positive effect of gasification pressure on exergetic efficiency also for waste biomass: MSW and sludge,

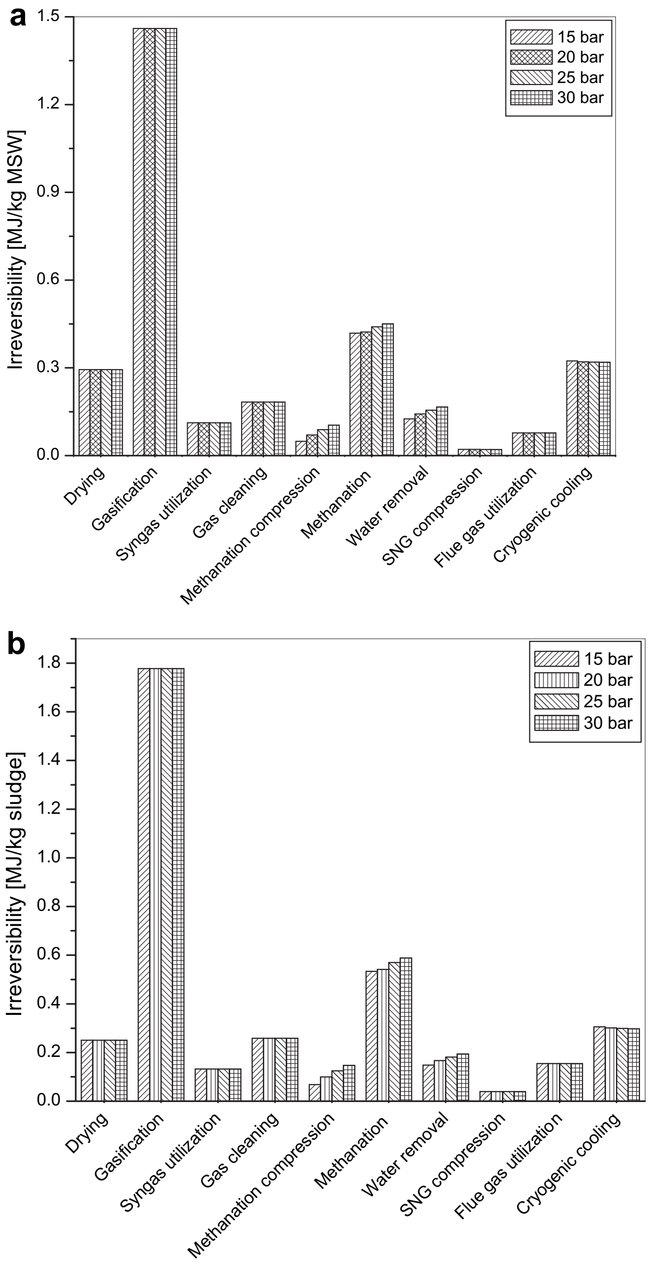

Fig. 9. Effect of methanation pressure on internal exergy losses in process units (at standard process conditions) for: a) – MSW, b) – sludge.

similarly as for woody biomass. The results shown in this figure are for the standard process condition for waste biomass: methanation pressure 30 bar, and temperature in the 1st methanation reactor (MR) 500 °C. The explanation of the positive effect of gasification pressure on exergetic efficiency for waste biomass is similar to that given in Section 4.2 for woody biomass, what is the increased SNG production rate and reduced exergy input to the process.

The exergetic efficiency for waste biomass is lower than that for treated wood whereas the exergetic efficiency for MSW is the lowest from all investigated biomass feedstock. MSW has also the lowest feedstock quality (see Table 1), that is the highest moisture and ash content, low hydrogen/carbon ratio and the lowest HHV (Higher Heating Value). The exergetic efficiency for sludge is between those for treated wood and MSW. Fig. 5a also shows that for waste biomass the specific process irreversibility (internal exergy losses) per unit volume of produced SNG decrease with gasification pressure, similarly as for treated wood. The specific irreversibility for MSW is the highest whereas those for treated wood and sludge are similar. It should be noted that the overall process exergy losses for sludge (and MSW) are lower than that for treated wood, but also amount of produced SNG for sludge (and MSW) are also lower.

Fig. 6a shows the effect of methanation pressure on exergetic efficiency for waste biomass: MSW and sludge. The results shown in this figure are for the standard process condition for waste biomass: gasification pressure 7 bar, and temperature in the 1st methanation reactor (MR) 500 °C. Also in this case the exergetic efficiency for waste biomass is lower than that for treated wood whereas the exergetic efficiency for MSW is the lowest from all investigated biomass feedstock, similarly to the results shown in Fig. 5a. However, contrary to treated wood, operating methanation unit at elevated pressure has negative effect for MSW and sludge. The explanation of this effect can be supported by the effect of methanation pressure on the irreversibilities of individual process units, as shown in Fig. 9a for MSW and Fig. 9b for sludge. For waste biomass: MSW and sludge irreversibility of methanation unit increases with methanation pressure, more pronounced than for treated wood (see Fig. 6a). In the case of MSW this effect is due to lower hydrogen/carbon ratio of MSW feedstock than that for treated wood. Consequently, CO/H_2 ratio in syngas is for MSW so high that water–gas shift (WGS) reaction (see Eq. (5)) occurs in a considerable extent, which leads to the increase of CO_2 content in the methanation effluent stream. In the case of sludge the hydrogen/carbon ratio is similar to that for treated wood. However, the 1st methanation reactor operates for sludge at lower temperature (500 °C) than that for treated wood (610 °C) which leads to more methane production in this reactor for sludge. Consequently, it increases intercooling duty due to higher adiabatic temperature rise. Additionally, more steam is supplied to methanation section for suppressing carbon formation, which also leads to higher feed heating load. These factors altogether increase methanation irreversibility. The increase of irreversibilities of methanation section for waste biomass is not compensated by the decrease of irreversibilities of CO_2 separation (cryogenic cooling) what is the case for treated wood (see Fig. 6b – Selexol separation). Fig. 6a shows increase of specific irreversibilities for waste biomass with methanation pressure, opposite to that for treated wood. The specific irreversibilities for MSW are the highest from all considered biomass feedstock.

Fig. 7a shows the effect of temperature in the 1st methanation reactor (MR) on exergetic efficiency for waste biomass: MSW and sludge. The results shown in this figure are for the standard process condition for waste biomass: gasification pressure 7 bar, and methanation pressure 30 bar. Similarly to the above discussed results the exergetic efficiency for waste biomass is lower than that for treated wood whereas the exergetic efficiency for MSW is the lowest from all investigated biomass feedstock. Temperature in the 1st MR has a slightly positive influence on the exergetic efficiency (for the temperature range 500–650 °C), opposite to that for treated wood. For all investigated biomass feedstock temperature increase in the 1st MR reduces irreversibility of methanation section, as shown in Fig. 7b for treated wood, Fig. 10a for MSW and Fig. 10b for sludge what is due to reduced reaction rates and cooling duties at increased temperature. However, for treated wood irreversibility of CO_2 separation (Selexol method) increases quite substantially with temperature in the 1st MR whereas this effect is much lower for waste biomass: MSW and sludge, where CO_2 is separated by cryogenic cooling. It can be observed from Fig. 7a that exergetic efficiency for waste biomass is slightly reduced at temperature in the 1st MR of 700 °C. Generally, concentration of CO and H_2 in methanation effluent increase with methanation

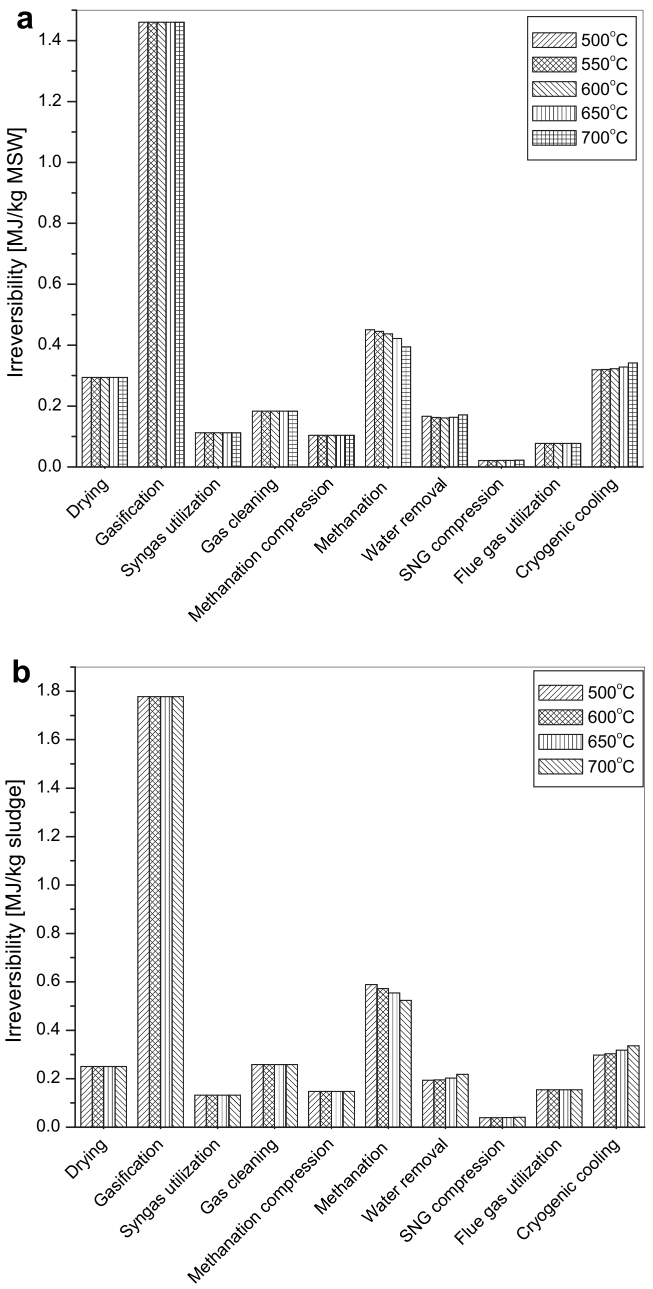

Fig. 10. Effect of temperature in the first methanation reactor on internal exergy losses in process units (at standard process conditions) for: a) – MSW, b) – sludge.

temperature due to chemical reactions (Eq. (1) and (2)) which are favored by lower temperatures. Consequently, methane content in SNG is reduced at higher methanation temperatures. At a certain point, which is 700 °C in this case, methane concentration is SNG is so low, that its exergy content reduces, what explains the decrease in exergetic efficiency at this temperature. Fig. 7a shows decrease of specific irreversibilities for waste biomass with the temperature in the 1st MR, opposite to that for treated wood. The specific irreversibilities for MSW are the highest from all considered biomass feedstock.

6. Comparison between various biomass feedstock

Table 4 summarizes typical major results of biomass-to-SNG process, including SNG composition and yield as well as exergetic efficiency, for all investigated biomass feedstock. Regarding SNG composition the main differences are in the content of CO_2, H_2, H_2O and N_2 whereas the content of CH_4 is in the same range 83–85 mol %. SNG produced from sludge and MSW has the highest N_2 content that corresponds to a high N_2 content in the feedstock (see Table 1). The high N_2 content in SNG from sludge is compensated by the low CO_2 content as these components do not have heating value. On the other hand a low value of N_2 in SNG from treated wood corresponds to a high content of CO_2 in this case. Table 4 also illustrates that CO_2 removal technology influences water content in SNG. At the temperature of cryogenic cooling all water is removed with the liquid phase due to its lower volatility compared to methane and CO_2. Thus SNG produced from MSW and sludge is water-free.

SNG produced from treated wood gas has the highest H_2 content due to high hydrogen/carbon ratio in this feedstock. For MSW, even though this feedstock comprises more carbon than treated wood, its hydrogen content is much lower. It leads to less H_2 content in the final SNG. Sludge gas similar to hydrogen/carbon ratio as treated wood but H_2 content in SNG is lower than that for wood for two reasons. Firstly, SNG from sludge has the higher CH_4 content than SNG from wood due to less CH_4 losses during CO_2 separation, and secondly due to the higher content of inert gases: N_2 and CO_2.

Treated wood, being the driest material with high carbon and low ash content, is the best feedstock for producing SNG. Table 4 indicates that approximately 25% of fresh treated wood can be converted to SNG. Sludge is the second rank with the SNG yield in the range of 15%. It is relatively wet with a high ash content which cannot be converted into combustible gas. MSW is at the lowest position due to higher moisture and ash content and lower hydrogen/carbon ratio than sludge. Only about 8% of fresh MSW can be converted into SNG, even after drying it to 10 wt% moisture content.

In term of exergetic efficiency, treated wood is at the highest rank, followed by sludge and MSW. This performance is mainly determined by feedstock composition. Treated wood has the lowest moisture and ash content and the highest organic fraction compared to MSW and sludge. The gasification of treated wood produces a larger amount of syngas with higher methane content and it is more efficient compared to waste biomass. Even though the performance of methanation and SNG upgrading units depends on syngas composition and operating conditions, it does not differ much for all feedstock. Therefore the overall plant efficiency is mainly determined by gasification.

Fig. 11 clearly illustrates that for all feedstock gasification contributes almost half of the total plant irreversibility. This happens mostly due to irreversibility phenomena in chemical reactions, including heat and mass transfer. Both methanation and CO_2 removal units give a considerable part to the total plant irreversibility. For all biomass feedstock methanation has a comparable contribution, which is about 14–15% of the total plant irreversibility. In case of treated wood, the contribution of CO_2 removal by Selexol absorption to plant irreversibility is higher than methanation since

Table 4
Typical SNG composition, yield and plant exergetic efficiency at a Wobbe-index of 44 MJ/Nm^3.

SNG composition		Treated wood	MSW	Sludge
CO	mole%	0.16	0.05	0.03
CO_2	mole%	7.70	6.49	3.19
H_2	mole%	6.54	3.03	2.47
H_2O	mole%	3.19×10^{-9}	–	–
N_2	mole%	2.40	5.00	9.45
CH_4	mole%	83.19	85.43	84.86
SNG yield	kg/kg wet feedstock	0.24–0.26	0.07–0.09	0.14–0.16
SNG yield	kg/kg dry feedstock	0.28–0.31	0.12–0.14	0.20–0.23
Exergetic efficiency Ψ	%	53.1–58.0	41.7–45.9	47.2–57.1

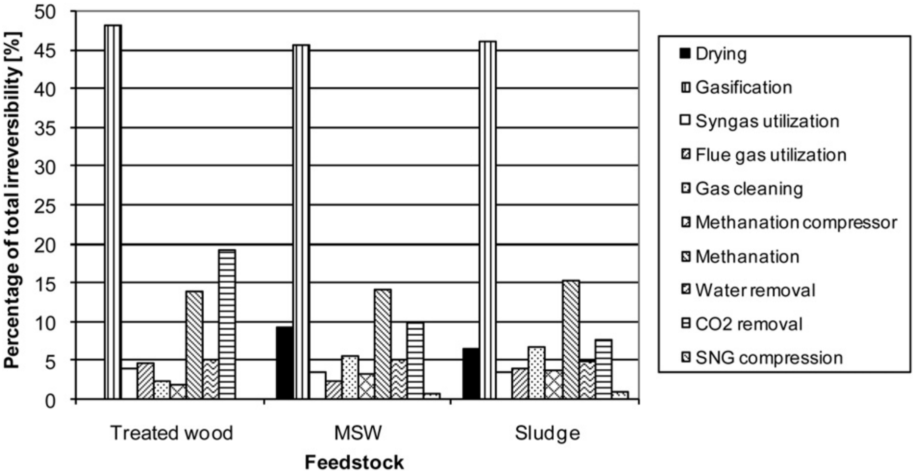

Fig. 11. Typical irreversibility distribution for treated wood, municipal solid waste and sludge.

it involves high operating pressure, which leads to relatively high methane loss. Comparing treated wood with MSW and sludge, it is noticeable that applying cryogenic cooling for CO_2 removal reduces exergy loss by approximately 50%. Drying of waste biomass has also been a substantial contribution to plant irreversibility. Other interesting phenomenon shown in Fig. 11 is the irreversibility in the gas cleaning step. Its contribution to plant irreversibility is higher for MSW and sludge due to their high impurities (S, Cl and F) contents.

7. Conclusions

Biomass, including virgin (treated wood) and waste biomass (MSW and sludge) can be converted into SNG (Synthetic Natural Gas) in a process combining indirect biomass gasification and subsequent methanation of produced syngas. The advantages of indirect biomass gasification are an allothermal operation without a need to use an extra heat and production of a nitrogen-free syngas. The overall biomass-to-SNG process consists of several process units, including not only biomass gasification, but also syngas cleaning and compression, methanation reactors, and conditioning of produced raw SNG, namely removal of water and carbon dioxide. Processing of waste biomass, which is more wet feedstock, is favored by feedstock drying directly before gasification. Removal of CO_2 from methanation effluent depends on biomass feedstock, being Selox absorption for woody biomass and cryogenic separation for waste biomass.

The study focuses on the evaluation of exergetic efficiency of this process for various biomass feedstock and process conditions. It is shown that exergetic efficiency depends on feedstock quality, being the highest for treated wood, followed by sludge and MSW. According to this, the highest SNG yield is obtained from treated wood, followed by sludge and MSW. Exergetic efficiency is favored by higher pressure in the biomass gasifier for all investigated biomass feedstock. On the other hand higher pressure in methanation reactors increases exergetic efficiency for woody biomass but it decreases efficiency for waste biomass. Similarly, lower temperature in the first methanation reactor increases exergetic efficiency for woody biomass but it decreases efficiency for waste biomass.

The results show that the largest internal exergy losses (irreversibilities) take place in the gasifier, followed by methanation section, separation of carbon dioxide from methane, and drying of waste biomass.

For the range of parameters studied in the paper the exergetic efficiency Ψ ranges from 53 to 58% for woody biomass, 47–57% for sludge and 42–46% for MSW. The specific process irreversibilities (internal exergy losses) for woody biomass range from 22 to 27 MJ/Nm^3 of produced SNG depending on process conditions. These values, when compared to the chemical exergy of produced SNG (e.g. 29.4 MJ/Nm^3 for SNG produced at gasification pressure of 1 bar), confirm the conclusion that a little bit less than half of chemical exergy of biomass can be converted into chemical exergy of SNG.

Finally, it should be stressed that exergy analysis gives only results concerning thermodynamic efficiency and the presented results will be helpful in further process development. It is also necessary to perform economic analysis as well as to demonstrate technical feasibility of this process in order to make a final judgment about process feasibility.

Acknowledgements

The project is sponsored by the Cartesius Institute in Leeuwarden, Friesland, The Netherlands .

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